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An Abstract of

Use of Sonoluminescence to Reduce Cavitation Damage

in Diesel Engine Bearings

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Sonoluminescence is the effect of producing light from sound and occurs when a gas bubble is trapped in a fluid filled cavity and is forced to collapse under a barrage of sound waves. Frenzel and Schultes discovered this phenomenon in 1934 while exposing acoustic waves to photographic plates. This effect was not well understood until 1988 when Crum and Gaitan discovered the necessary conditions for producing single bubble sonoluminescence in the laboratory.

The luminescence is a result of the bubble violently collapsing from sound waves and this shares a close association with vibratory cavitation. Cavitation erosion is known to cause damage to rotational machinery when the collapse is near to surfaces due to the

high pressures associated with bubble collapse. With these high pressures and temperatures there is a considerable amount of damage to the outside layer of a bearing, thereby, reducing its useful life.

An experiment was constructed to generate sonoluminescence in the laboratory in order to obtain a greater understanding of this phenomenon and its association with bubble cavitation. Most of the research was done to investigate how to obtain single bubble sonoluminescence under different conditions and to determine how to detect it. Success in this has inspired several theories on how to use the methods for generating sonoluminescence to control cavitation in fluids under industrial conditions.

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Chapter One

Introduction to Sonoluminescence

Sonoluminescence is the effect of producing light from sound and occurs when a gas bubble is forced to collapse under a barrage of sound waves and in doing so emits bright flashes of light. Single bubble sonoluminescence (SBSL) occurs as a bubble is trapped in a fluid filled cavity where sound waves generated by opposing piezoelectric transducers are used to apply pressure to induce the bubble to cavitate[1]. The aim of this thesis is to investigate this phenomenon of SBSL and its association with cavitation which is known to cause extensive erosion damage.

The Royal Navy hired the English physicist Lord Rayleigh in 1917 to study the degeneration of ship propellers. Rayleigh determined that the small bubbles of air created by the propeller as it slices through the water were collapsing on to the blade surface with a force greater than 10,000 atmospheres. Lord Rayleigh was mistaken in one regard, he assumed the collapse of the bubble obeyed Boyle's Law, in which the temperature inside the bubble remains constant. It turns out that the collapse is so rapid that the process is virtually adiabatic, without loss to its environment producing very high temperatures within the bubble[2].

In the 1920's and 1930's scientists made public the work to develop sonar during World War I. In this body of work a strange phenomenon was noticed in which a strong sound field could catalyze reactions that take place in an aqueous solution[2]. Sonoluminescence was discovered in 1934 when Frenzel and Schultes at the University of Cologne exposed a photographic plate to acoustic waves generated in a water bath and observed a darkening of the plate[3]. In the late 1950's and early 1960's some experimentation was done in an attempt to find a relationship between the phase of sonoluminescence and the sound field, however with few results. Little else was done to investigate this phenomenon and interest was lost until the 1980's, Ref. 4.

In 1988 after an extensive search Crum and Gaitan discovered the necessary conditions in which single bubble sonoluminescence (SBSL) occurs. To produce SBSL in the laboratory they found is was necessary to levitate a gas bubble in an acoustic field between the nodal and antinodal regions of the standing wave field. The acoustical pressure force balances the buoyancy force and as the pressure amplitude is increased the bubble will undergo non-spherical pulsations. If the fluid that is used to suspend the gas bubble is sufficiently degassed then the bubbles motion will stabilize and emit a faint glow. This luminescence that is observed is not a result of the sound field directly but is bubble cavitation induced by the sound waves. Based on the current results the temperature inside the collapsing bubble may reach in excess of 10^5 K with a pressure greater than 10^7 bar, Ref.3.

The frequency range for the necessary generated vibration of the piezoelectric transducers for SBSL to occur is approximately 25 to 30 kHz[3]. This is in the ultrasonic range, i.e., ultrasonic (any frequency above 20 kHz) which is the maximum level for human hearing. The shape and size of the chosen flask and its contents determine the frequency necessary for SBSL. Ultrasonic devices are commonly found being used for nondestructive testing and the cleaning of fine machine parts and instruments[5].

The light emission implies existence of high local temperatures enough to incandesce gas and influence chemical reactions. The luminescence results from the collapse of bubbles in the sound field in which the bubbles obey spherical symmetry, at least until the final stages producing extremely short bursts of light[3].

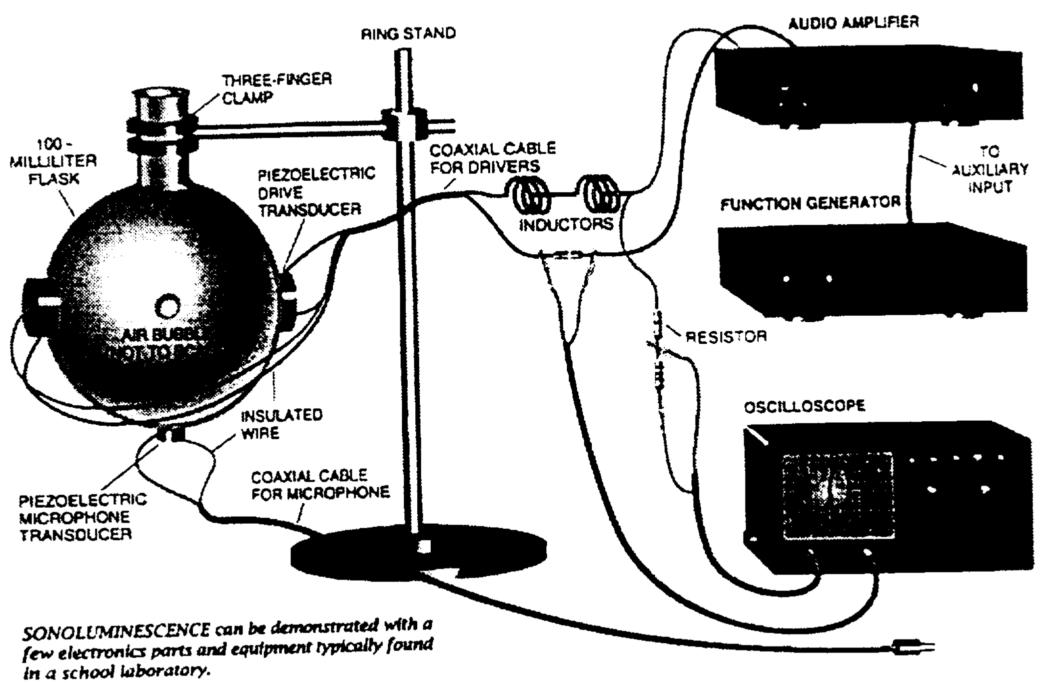

Figure 1.1: Diagram of UCLA sonoluminescence experimental setup.

Also in the mid 1980s a group of researchers at UCLA led by Seth Putterman including his students Bradley Barber and Robert Hiller began studying sonoluminescence. Dr Putterman's motivation grew from his discussions with Thomas Erber of the Illinois Institute of Technology on whether the Navier-Stokes equations could be used to explain how sound could be used to make light. Perhaps due to his disbelief that this was even possible he was not just motivated to produce SBSL in the laboratory but to attempt to answer many of the questions regarding sonoluminescence. Some of these early questions were how long was the duration of the flashes, how predictable was the flash rate and what the radius of the bubble was throughout its cycle? Putterman searched the old papers on the subject and also learned others had recently began to study this strange phenomenon. After receiving information from Crum and Gaitan, the UCLA group assembled their own apparatus and began to make measurements with a laser and photomultiplier tube. Figure 1.1 contains the diagram of the experimental setup used by the UCLA group to produce SBSL as it appeared in Scientific American[2].

Their investigations revealed that the flash lasted with an upper bound of about 50 picoseconds and occurred with incredible clock like regularity with about 35 microseconds between flashes. This value for the timing between flashes varies by no more than 40 picoseconds. The bubble's radius begins its cycle at around 50 microns (approximately the diameter of a human hair) and decreases to about 0.5 microns where the light is emitted as the bubble decelerates because it cannot become any smaller due the repulsive force of the gas atoms and molecules. A graph of the bubble's radius and the acoustic force on the bubble throughout the sonoluminescence cycle is shown in Fig. 1.2 as determined by Putterman's UCLA group. Notice how steep the slope of the bubble's radius as it collapses right before the light flashes. The shock waves that are formed inside the bubble is one theory for the light production.

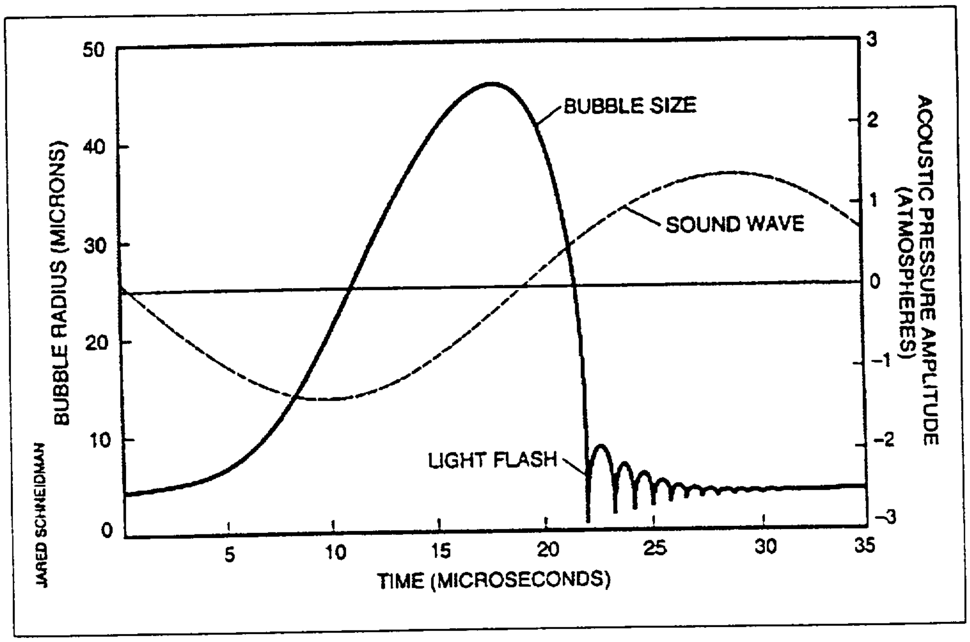

Figure 1.2: Bubble radius and acoustic force during the SBSL cycle.

An intense area of study by the UCLA group has been to determine the cause of the luminescence and what can be done to increase its output. After much experimentation it has been found that producing SBSL is very dependent on the gas concentration of the bubble, the ambient temperature of the fluid and the makeup of the surrounding fluid. Some of these are not just required to produce SBSL but will increase its output significantly when properly adjusted to the correct parameters[2].

Robert Hiller at UCLA, in 1991 also performed research to determine the temperature achieved during SBSL. Even though the cavitating bubble emits a light blue light and resembles a faint star in the night sky he found that much of this radiated light is located in the ultraviolet light region. He measured the spectrum up to an ultraviolet wavelength of 0.2 micron but could not continue further because energy above six electron volts cannot propagate through water. At six electron volts the corresponding temperature is 72,000 K, so the interior of a sonoluminescencing bubble must be scorching.

It is thought that the bubble collapses from a high concentration of mechanical energy from the sound waves causing the liquid to fail under tensile stress inducing a chemical reaction. As the cavity of gas collapses a strange phenomenon occurs within the cavitating bubble. The most obvious being the luminescence of the gas and another being possibly a high local temperature in the range of thousands of degrees Kelvin. This high temperature region is thought to be confined to a very small area since there is no noticeable change in the ambient temperature of the liquid[3].

There has been much effort to determine the value of this temperature since it is assumed to be very high to produce these flashes of light. In 1986, the temperature of a collapsing bubble was estimated at around 5000 K by Ken Suslick at the University of Illinois using chemical rate equations. In 1993, Andrea Prosperetti of Johns Hopkins University using sophisticated computer models of a collapsing bubble estimated the temperature to be approximately 7000 K or around the surface temperature of the Sun[6].

Extensive work has also recently been done at Lawrence Livermore Laboratory by William Moss, Mike Moran and a group of researchers investigating the internal temperatures of the cavitating bubble during SBSL. If the temperature can be determined this will provide insight into the pressures being generated within the cavitating bubble since they are directly related. Numerical calculations were performed with a predicted temperature reaching one kilovolt (10^7 Kelvin) with the hope of achieving micro-thermonuclear fusion during sonoluminescence in a bubble filled with deuterium gas, a commonly found isotope of hydrogen. Even though the project is theoretical, Moss et al[7] believe through their simulations it may be possible to enter the region where a small amount of thermonuclear fusion could be obtained with sonoluminescence.

As can be noted from the history of sonoluminescence it is not a new idea and a considerable amount of research work has been done in just the past few years. However, there are still many unknown questions related to this phenomenon. There are numerous possibilities for future applications with the high temperatures and pressures produced by sonoluminescence inside the cavitation bubble.

Chapter Two

Sonoluminescence Theory

As the name sonoluminescence implies it is the science of light produced from sound and even though it has a long history most of the discoveries and advances have occurred in just the past few years. Since Crum and Gaitan performed their initial experiments to produce SBSL in the laboratory it has fueled a large effort to fully understand this phenomenon and put these theories to work in applications. Some of this effort is not just to understand why sonoluminescence occurs but what can be done to overcome the very tight constraints that must be met to produce sonoluminescence in the laboratory and increase the intensity. Perhaps the high temperatures and pressures associated with cavitating bubbles that cause extensive damage in machinery could be applied to take advantage of these large forces.

During the SBSL cycle the gas bubble trapped in the acoustical field undergoes an expansion and compression cycle in which the radius of the bubble changes very rapidly. The bubble starts out the size of several microns under ambient conditions, then as the pressure drops during the expansion part of the sound field the bubble increases to a radius of about 50 microns. When the expansion is complete the inside of the bubble is nearly a vacuum but the external ambient pressure is still acting on the bubble surface to cause a catastrophic collapse. As the radius of the bubble decreases to about 0.5 microns the surface can no longer continue its inward rush due to the repulsive force between the gas atoms and molecules. The light flashes occur as the bubble decelerates during the final stages of the collapse as the bubble reaches its minimum radius. This compression rate is equivalent to taking the volume of air found in a small room (1000 cubic feet) and decreasing it to about the size of a pack of cigarettes all in less than 35 microseconds. The bubble's radius is plotted with respect to the acoustical pressure as the sonoluminescence threshold passes from the lower boundary to the upper during a single SBSL cycle in Figure 2.1. Notice how the average radius of the bubble increases with acoustic pressure but the point at which sonoluminescence (SL) occurs suddenly ends, Ref. 2.

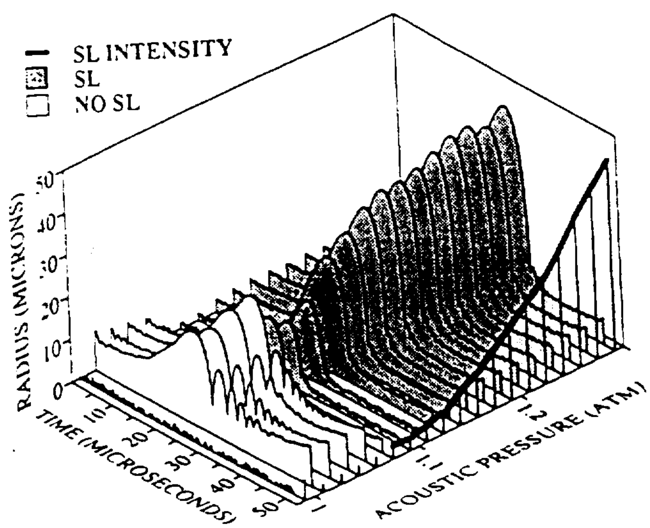

Figure 2.1: Bubble radius through the SBSL cycle according to acoustic pressure.

According to the strong shock wave theory of sonoluminescence, an imploding spherical shock wave is sent through the bubble as it collapses supersonically. The power of this shock wave increases to infinity as its radius decreases to zero[8]. A shock wave is a zone of extremely high pressure within a fluid and can propagate through the fluid at supersonic speeds. Shock waves are formed by a sudden and violent disturbance in a fluid[5]. It has been suggested that luminescence occurs from a shock wave in the bubble rather than the adiabatic heating of the gas. This shock wave is produced from the acoustical forces in the sound wave generated from transducers (refer to Figure 1.1) causing the bubble to fail under tensile stress. The acoustic force is small enough that the bubble remains symmetrically spherical from the surface tension as it collapses until it reaches its final stages. During the final stages it is thought a spike will form from the imploding shock wave and pierce the opposite side of the bubble producing the flash of light. During the symmetrical phase of the collapse the gas inside the bubble remains relatively cold with the high temperatures appearing at the final stages[3]. Figure 2.2 shows an animated series of frames containing a bubble collapsing, beginning with formation of the shock wave at the bubble's wall until its final collapse.

There has been several different theories formulated to account for the production of light during the SBSL cycle from the ionization of the gas within the bubble during the collapse and shock waves travelling through the bubble. One of these theories, due to Wu and Roberts of UCLA, is based on the idea that the heating inside the bubble occurs in a very short period of time, in line with the flash duration. There is an enormous amount of energy released during cavitation in which they believe a shock wave is formed as the bubble inwardly collapses moving faster then the speed of sound. This energy is then distributed across a very small volume within the center of the bubble. Since only the molecules at the very center of the bubble are affected it gives them a higher concentration of energy. Consequently, they bounce against one another causing the shock wave to rebound outward. During the implosion, the gas in the bubble is heated quite rapidly, but it also cools very rapidly during the expansion as the shock wave rebounds. Wu and Roberts theorize that shock waves are the source of the flash of light and high temperatures produced during sonoluminescence[7].

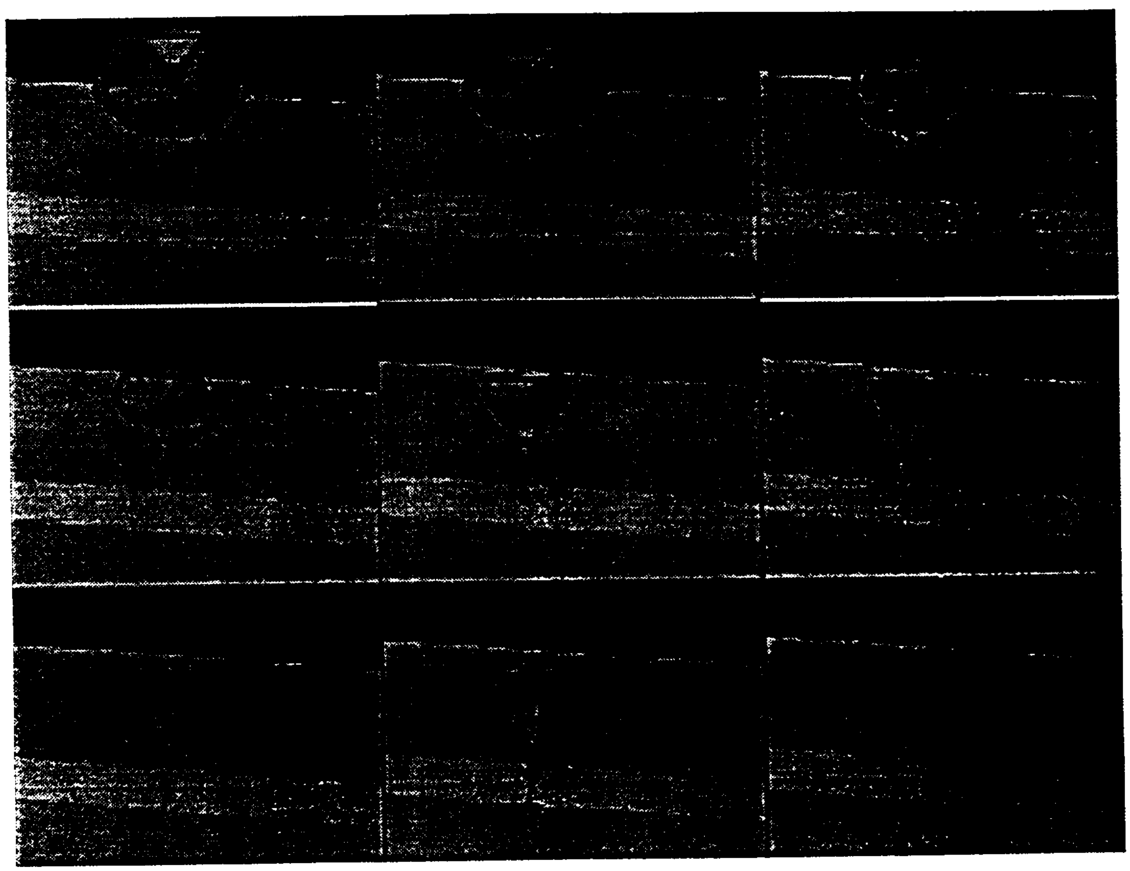

Figure 2.2: Animated pictures of a shock wave travelling through a collapsing bubble.

More evidence has been recently presented supporting the shock wave theory by the Putterman group at UCLA when measuring the entire spectrum of colors during sonoluminescence for mixtures of various gases. As the collapsing bubble launches a shock wave it heats up the bubble forming a dense, relatively cold plasma producing light through a process called "thermal Bremsstrahlung". This occurs when the plasma electrons collide with each other as they speed up and slow down at various rates producing light of all different colors. This rules out the adiabatic heating hypothesis which states an imploding bubble would first emit red light and would gradually shift to higher energy colors as the bubble collapses producing higher temperatures[8]. They also made their temperature estimates by measuring the spectrum of light given off from the cavity during SBSL. Figure. 2.3 shows that SBSL emits a continuous wavelength in the ultraviolet spectrum that gets cut off at approximately 200nm. It gets terminated at this wavelength because light energy above this region cannot propagate through water and plain glass.

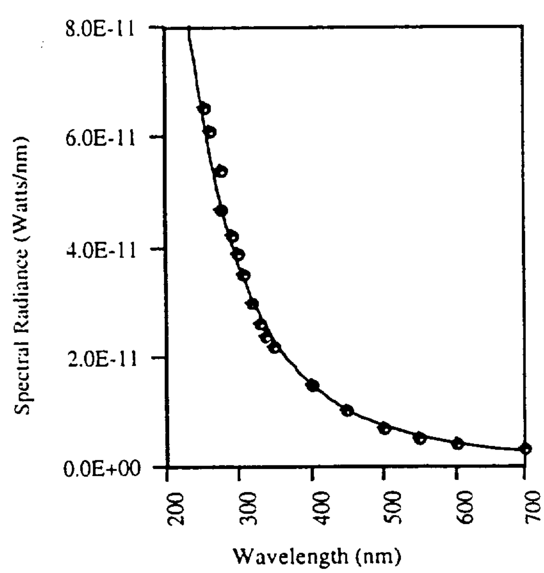

Figure 2.3: SBSL light spectrum measured by Putterman's group.

Putterman estimates if the shock front remains intact to a radius of 0.1 micron from the center of the cavity then the temperature could reach nearly 100,000 K as measured from the ultraviolet spectrum. If the shock front could survive to a cavity radius of 0.02 micron then the temperature could reach upwards of 1,000,000 K, Ref. 2.

There has been research dedicated to increasing the output of the cavitating bubble in terms of its ability to produce light during sonoluminescence. Stabilizing the bubble and increasing the brightness of the luminescence during SBSL not only makes it easier to reproduce but also easier to identify when it is occurring. The wavelength of the sound produced by the transducers is much larger than the radius of the bubble, so the acoustic force exerts a uniform stress on the surface of the spherical bubble. During stable SBSL the gas bubble emits picosecond flashes of ultraviolet (UV) light with incredible regularity. The point made about stability is that if an unstable bubble is trapped in an acoustic field, as the amplitude is increased the bubble will just collapse and dissolve into the fluid without emitting any light[9].

The brightness of the flash is very sensitive to the composition of the gas mixture within the bubble. It has been found that doping the gas with a noble gas such as argon, helium or xenon could increase the UV output. This was proven by experiments done with bubbles solely composed of N_2, which produced SBSL with a light 20 times less intense than a bubble containing air. Similar results were noted with a bubble composed of O_2 and a mixture of both N_2 and O_2. When the gas mixture contains 1% Argon and the remaining amount of N_2, the light emission is increased by a factor of 30 over a bubble composed only of N_2. Air normally contains a concentration slightly less than 1% argon so these findings are not completely unexpected[9].

For SBSL to occur it is necessary to degas the water, that is, to decrease the concentration of air that is dissolved in the water. Either boiling the water or using a vacuum pump to decrease the air pressure within the holding flask will degas the water. Water seems to be the best liquid for SBSL due to its low solubility of gases. It is still possible to produce sonoluminescence in liquids other than water but they require the use of gases that are less soluble than air such as H_2 or He, Ref. 9. Brenner has determined for stable SBSL in water with an air bubble it is only necessary to degas the liquid down to $p_\infty/P_0 = 0.1 - 0.4$. For SBSL in an Argon bubble the liquid has to be degassed to a greater degree of $p_\infty/P_0 = 0.004$. For both these cases $P_0 = 1$ atm. Ref. 10. Moss has proposed that the nitrogen and oxygen molecules in the collapsing air bubble dissociate forming products with the surrounding fluid leaving behind only argon and water vapor to produce the light. Their model calculates a light spectrum for SBSL for pure argon, which closely matches the experimental spectrum for a collapsing air bubble[11].

Crum and Matula have performed experiments supporting Brenner's proposal that a sonoluminescence bubble is a "chemical reaction chamber" that rapidly converts the nitrogen and oxygen present in air into chemically active species. These species will eventually leave the interior of the bubble leaving behind mostly water vapor and the non-reactive argon, which provides the source for the light emissions. So below the sonoluminescence threshold the bubble remains a concentration of air but once it is driven above the SBSL threshold the bubble is converted to a mostly argon bubble. This transition appears to take only a few seconds. This process may also explain the differences between SBSL and multi bubble sonoluminescence (MBSL) which involves the collapse of many bubbles. Since this process takes several thousand cycles to rectify the argon the MBSL bubbles do not survive long enough for the conversion to occur. This could explain why the light produced during MBSL is much less intense[12].

Another parameter that seems to have an effect on the intensity of the light produced during SBSL is the temperature of the host liquid. Lowering the temperature of the water in the flask from 35 to 1°C will increase the emission by a factor of over 100. This effect is believed to happen because water dissolves about twice as much air at 0°C than at room temperature, Ref. 9.

As was stated earlier, the luminescence during bubble collapse is an indication of high temperatures and pressures within the bubble. A method used to determine the temperature is to measure the light spectrum emitted during the sonoluminescence cycle. The spectral bands show characteristics of the host liquid and it is necessary to resolve recognizable emission bands generated by atomic and molecular transitions. With the right amount of dissolved argon in the water the spectrum of dodecane, which is an organic liquid, was measured. It produced a synthetic spectrum indicating an effective temperature of the C_2 excited state at 5100 K during MBSL[3]. The main difference between SBSL and multi bubble sonoluminescence is that SBSL has a much higher light intensity and it also is just one bubble oscillating for billions of cycles without dissolving or changing its average size[13]. With SBSL the spectrum does not appear to have any spectral bands or emission lines that are comparable to a synthetic spectra. The bands may be there but could be so broad by the high temperatures and pressures that they do not indicate any well-known atomic and molecular transitions and could be approximated by that of a blackbody. With measurements taken by a spectroscope of a SBSL in water and compared to the blackbody spectrum it revealed an effective temperature of 16,000 K. When the water temperature is cooled the temperature inside the bubble was estimated at 30,000 K when the SBSL spectrum was still compared to a blackbody. Even though these temperatures seem very high, due to the symmetrical nature of the imploding bubble, temperatures much higher than these in the range of 10^8 K could be reached which would result in some very interesting physics and chemistry[3].

Lawrence Livermore Laboratory has lead the way in investigating the high temperatures within a bubble during sonoluminescence. Their objective was to determine if the temperatures and pressures were great enough to trigger a fusion reaction. It is thought with enough power, an atom of deuterium, or heavy hydrogen the most common form, could be fused together. A very large laser known as Nova was constructed at the cost of a hundred million dollars to generate large temperatures and pressures to study nuclear fusion. A sonoluminescence assembly can be constructed of materials costing about two thousand dollars with a good deal of the materials needed found in most engineering laboratories[14]. Even though producing a fusion reaction with this method seems remote due to stability of the imploding shock wave, which limits the concentration of energy, the simple and inexpensive process of sonoluminescence could be used to obtain information about inertial confinement fusion[3].

Nuclear fusion is the process by which the Sun produces its energy, to warm the earth. The Sun is primarily composed of hydrogen and helium and at the center, known as the solar core, the gravitational force is very large, producing pressures greater than 1 billion atmospheres and a temperature of about 15×10^6 K. At the solar core, where the density is 100 times that of water, there are forces great enough to fuse the nuclei of deuterium and form helium nuclei. In this process an enormous amount of energy is released and with hydrogen being the most abundant element in the universe if it could be performed on earth it would provide an almost unlimited amount of power[5].

As it can be easily noted producing fusion in the laboratory has proven to be very difficult due to high pressures and temperatures necessary for the reaction. Wu and Roberts calculated under the most ideal condition temperatures could reach 10^8 K during SBSL but Moss at Lawrence Livermore Laboratories using a computer model estimated that a temperature of 2×10^6 K could be reached. This is about half of what is needed for a fusion reaction more likely to be produced in a laboratory. What is more important is the pressure produced by an imploding shock wave which could be in the millions of atmospheres, which is the point at which the density of the gas approaches that of a typical metal. Even at these incredible temperatures and pressures fusion may not be achieved in the laboratory from sonoluminescence. Table 2.1 contains the fundamentals of sonoluminescence that have been determined to date. This is just the compiled data of bubble size, cycle time rate, amplitude of light emission and the power levels achieved based on blackbody assumptions determined by the UCLA group.

Light Emission	
6×10^6 photons (at 20 °C)	
Time Scales	
Flash Length	<50 ps
Period	22 μs-50 μs (20 kHz-45 kHz)
Jitter	<50 ps
Blackbody Assumptions	
25,000 K-1,000,000 K	
4.3×10^{-8} watts - 7.2×10^{-4} watts (average power)	
3.2×10^{-2} watts - 533 watts (peak power)	
Bubble Dynamics	
Bubble Radius	5 microns->50 microns->0.5 microns

Table 2.1: Fundamentals of Sonoluminescence.

One way to increase the temperature and pressure with sonoluminescence would be to add an impulsive force to the bubble just before the shock wave is launched which would increase the compression of the gas. Another method to increase the gas compression would be to lower the frequency of the sound wave which would allow the bubbles to grow larger and perhaps more energy could be extracted during the compression. Currently SBSL operates at tens of thousands of cycles per second so the bubble has very little time to grow after each compression cycle. Large bubbles have a disadvantage because gravity causes a nonsymmetrical collapse of the bubble so the focus of the energy would not be in the center producing diminished results. If an SBSL system is constructed in a micro-gravity environment perhaps other conditions could be met to produce larger bubbles and/or compression rates to derive enough energy to sustain a fusion reaction[6]. Recently sonoluminescence experiments have been flown aboard the NASA micro gravity research airplane better known as the "Vomit Comet", but no results have been made available yet. Even if the sonoluminescence phenomenon never obtains fusion maybe it will provide insight to the chemical and physical reactions taking place on these large scales.

Chapter Three

Cavitation Erosion

Cavitation is the term associated with the phenomenon of the rupture of liquids and the name implies the motion of cavities of gases in liquids. As mentioned earlier cavitation occurs when a cavity of gas fails under tension in a liquid when an external source of energy is applied. This tension can appear in fluid flow, such as ship propellers (as Lord Rayleigh studied earlier this century), hydrofoils, bearings, pipes and pumps. The energy to produce cavitation does not just come from the friction generated in fluid flow but may also be produced from a sound field and by light energy. Cavitation is accompanied by a number of effects such as emitting shock waves, light, eroding solid surfaces and inducing chemical reactions[15].

Cavitation occurs when vapor bubbles form in the low-pressure regions of fluids that have been accelerated to high velocities. These cavities are formed by static or dynamic means and are a liquid phenomenon, they do not occur in either solids or gases. Cavitation is commonly found in machinery components such as centrifugal pumps, turbines and propellers. The bubbles are formed when the pressure in the fluid has been reduced to its vapor pressure and will expand as the pressure continues to drop but will suddenly collapse "implosively" when they come in contact with a high-pressure region. It is this implosion that makes cavitation undesirable because these sudden collapses of vapor cavities cause extreme pressure that can erode rotating blades, pit metal surfaces from the high pressure collapse, cause additional vibrations and reduce operating efficiencies from the distorted flow[16,17]. Figure 3.1 shows damage done to a plate exposed to ultrasonically induced transient cavitation in a heavy water reaction vessel.

Figure 3.1: Cavitation damage to a metal plate from cavitation bombardment.

Acoustic cavitation is the formation and pulsation of cavities filled with either vapor or gas in a liquid under acoustic stress. Cavitation has been classified further to occur as two general types: transient and stable cavitation. Transient cavitation refers to events that last only a fraction of a second. They usually occur at high-pressure amplitudes and are attributed to vapor and gas bubbles that first expand during the negative part of the pressure cycle, then collapse. Transient cavities are not necessarily unstable; they tend to collapse very rapidly producing surface instabilities that often result in their destruction[4]. Transient cavitation is generally not expected to last more than a few cycles and is probably the type most responsible for damage that occurs during cavitation[17].

When a bubble collapses it occurs very rapidly but under acoustic pressure the bubble will first grow to some maximum radius until the ambient pressure stops the expansion and then collapse. It is during this expansion of the bubble that work is done. When the collapse is non-spherically symmetrical a flat solid surface nearby causes the bubble to involute from the top and to develop a high-speed liquid jet towards this surface. When this jet hits the opposite bubble wall it pushes against the wall causing a protrusion out of the bubble. Figure 3.2 shows a photograph of a liquid jet produced by a collapsing cavitation bubble, the actual diameter of the bubble is about 1 mm. This protrusion continues until the energy from the jet is used up. When the protruding jet has elongated to its maximum length the gas and vapor becomes unstable and decays with the main bubble surface returning to its former spherical shape. It has been hypothesized that this process also occurs with sonoluminescence whereby light is generated from this jet as it passes through the opposite side of the bubble wall during bubble collapse. The collapse at the tip of the jet is much faster than the collapse of the main bubble and the most violent compression may occur in the main bubble producing the light. There are usually at least three shock waves produced during a collapse, two from the jet and a third when the bubble reaches its minimum size. The main bubble collapses in the shape of a torus with questionable stability and may actually emit several shock waves[15].

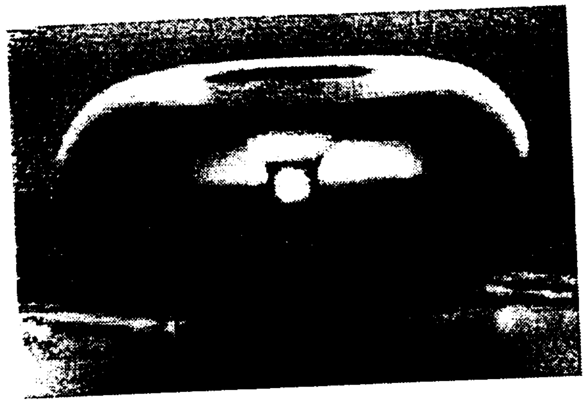

Figure 3.2: Liquid jet travelling through a cavitating bubble.

Cavitation usually occurs in a field of bubbles and has the appearance of a rather blurry mass of foam. The cavitation itself is seldom seen because it occurs within closed opaque conduits. The effect appears blurred to the eye or in a photograph because cavitation is a high-speed phenomenon occurring too fast to be seen by the eye or captured in a photo without a special high-speed camera[17].

Cavitation has associated with it many different stages with the first being incipient cavitation which occurs when the cavitation is barely detectable. During this stage the bubbles are very small and the zone in which the cavitation occurs is limited. When conditions are beyond the threshold or boundary at which cavitation has fully developed the desinent stage has been reached. The conditions that define which type of cavitation is occurring is dependent on type of liquid used, whether the fluid includes contaminants and on the pressure field in the cavitation zone[17].

Cavitation has been classified into four basic types based on its principal physical characteristics. The first type is traveling cavitation in which the bubbles move along with the liquid as they expand, shrink and collapse. The second is referred to as fixed cavitation because sometime after inception the liquid flow detaches from the rigid boundary of the immersed object to form a pocket or cavity attached to the boundary. Sometimes these pockets can become very developed and extend well beyond the body and is defined as supercavitation. The third type is vortex cavitation and is found in the cores of vortices that form in zones of high shear forces. This is the type associated with propellers and can occur with open or ducted blades while approaching steady state conditions. The fourth type is vibratory cavitation and is found under no flow or very low velocity flow conditions. In this form the forces causing the cavities to collapse are due to a continuous series of high amplitude and high frequency pressure pulsations. With this type the pressure variations have to be great to cause the pressure to drop below the vapor pressure of the liquid. Vibratory cavitation occurs with either surfaces that vibrate or from devices specifically designed to produce pressure waves such as transducers. An example of surface vibration occurs when pressure waves are generated by an engine's natural frequency either at speed or idle. If the amplitude is large enough cavitation can be produced as the cylinder wall is vibrated. Vibratory cavitation is also the type associated with producing the sonoluminescence phenomenon from piezoelectric transducers[17]. .

The effects of cavitation are very undesirable in hydraulic equipment requiring the need to either control or avoid cavitation when designing machinery. These limitations are necessary because cavitation will modify the hydrodynamics of the flow and damage solid boundary surfaces in the flow. As it has been previously stated all types of flows are affected by cavitation and if the phenomenon is ignored equipment performance may be seriously affected and its life shortened. Cavitation is most often associated with water because of its universal use in industry but it can be found in all liquids including molten metals, cryogenics and petroleum products[17].

The hydrodynamics of a fluid is affected by cavitation as the gas in the cavity displaces the liquid, the flow pattern is modified and the interaction between the liquid and its boundaries are altered. Cavitation will generally increase the overall resistance of the flow, will generally limit the thrust of a ship's propeller and will lower the performance of a turbine by decreasing the power output. In any case cavitation imposes limits on output and decreases hydraulic equipment efficiencies[17].

Cavitation damages solid boundaries by simply eroding material from the surface. All materials are susceptible to cavitation erosion including all metals, hard or soft, rubber, plastic, glass, quartz and concrete[17]. Nearly all materials during the initial stages of cavitation known as the incubation period exhibit no noticeable amount of erosion. After this initial period erosion damage increases very rapidly eventually leveling off to a linear rate of damage. To illustrate how quickly the damage can occur Figure. 3.3 shows a scanning electron micrograph of a brass plate after just a few shocks. Some materials are more resistant to erosion from cavitation such as stainless steel and aluminum bronze, whereas soft metals like brass or mild steel will erode more rapidly. Eventually after the surface becomes pitted and heavily damaged the rate of erosion decreases significantly. When cavitation occurs in a corrosive fluid the damage is highly accelerated due to any protective films or oxidation that are eroded away creating ideal conditions for corrosion to occur[18].

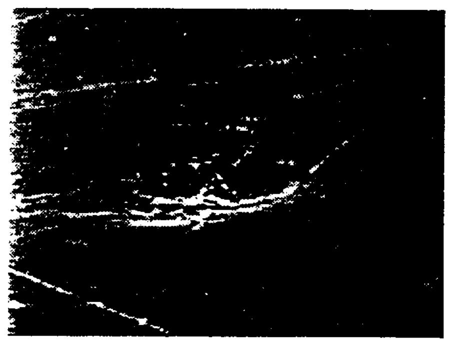

Figure 3.3: Cavitation damage to a brass plate after just a few cycles.

The difficulty with cavitation is identifying when it is taking place. In most cases it occurs in a cloud of bubbles obscuring the view of the bubbles that are coming in contact with the high-pressure region causing the collapse. One clear indication is the considerable amount of noise that is generated by the collapsing cavities, some in the human hearing range, some in the ultrasonic region. The problem associated with this identification method is the machinery producing the cavitation is often much louder that the noise from the collapsing bubbles themselves. There is an important link between cavitation and noise, collapsing bubbles always produce noise, submarines designed for their quietness can generate more noise from the cavitating bubbles of the propellers than from the ship itself[17]. Placing a rapidly vibrating surface, near a specimen, submerged in a fluid can induce cavitation erosion of a surface. A piezo-electric transducer operating around 20 kHz will cause intense localized cavitation. For studying cavitation an acoustical setup is ideal for experimentation due to the fact that the sound waves from the transducers are beyond the range of human hearing. Consequently, any sounds produced will be from the cavitating bubbles. Listening for the point of loudest cavitation the optimum frequency can be determined[19].

Cavitation usually does not repeatedly occur in the same spot but over a specified region and damage will occur over that entire region. Cavitation does not occur very near the point of origin but usually occurs in a zone downstream of the minimum pressure region. Experiments have proven that this distance can be determined and most of the damage caused by collapsing cavities occurs at the downstream end of the cavitation zone[17].

The pits produced by cavitation on a boundary surface are spherical in nature and are similar to indentations made by a hardness tester. It is assumed that the energy from the collapsing bubble is equal to a ratio of the volume of a spherical pyramid whose base is the pit surface to the total volume of the sphere. A simple model of this geometry is shown in Figure 3.4 where the energy released is transmitted spherically outward. Surface tension is neglected and a complete collapse of the bubble is assumed, the initial size of the bubble may be calculated from Rayleigh's basic assumption that work done by the fluid during collapse must equal the collapse energy.

The collapse of the bubble will begin when the local pressure rises above the vapor pressure and the cavitation occurs near the surface. It is assumed the collapse is complete when the average pressure is half the stagnation pressure above the vapor pressure. This model gives the general idea of the energy release from a collapsing bubble and pit formation. Some important features are ignored in this model such as nonsymmetrical collapse due to the close proximity to the wall and the fraction of collapse work absorbed in forming the pit will be a simple constant even for radially symmetric shock waves[17].

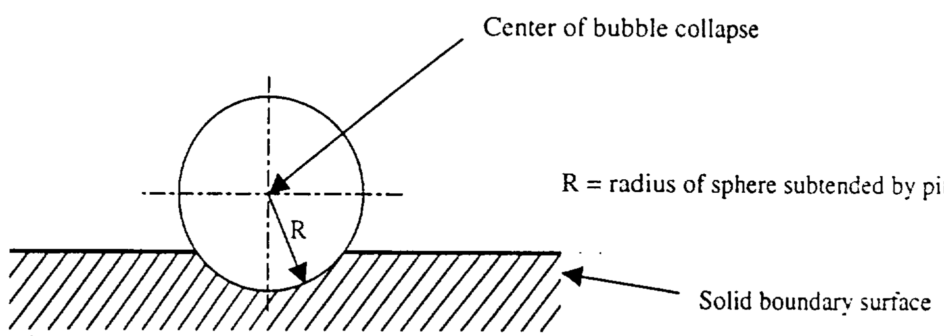

Figure 3.4: Spherical segment pit model.

Cavitation damage to engine bearings has received considerable attention during the last few years due to the design trends of higher rotational speeds and high cylinder pressures. Cavitation erosion of engine bearings is predominantly seen in diesel engines because of the more severe combustion process. Diesel engines also have more complex oil feeding arrangements, causing greater flow discontinuities and providing more vaporous cavities to be formed in the lubricant. The loss of lining material around the bearing due to erosion reduces reliability and life of the bearing[19].

A common form of bearing damage from cavitation erosion has been found on both fully grooved and partially grooved large end bearings. The damage will occur predominantly on the groove edges, but can spread to the bearing lands of fully grooved bearings. For the partially grooved bearings most damage occurs at the groove run-out, either at the end or the side of the run-out. The same type of damage has been recorded for partially and fully grooved main bearings. As high operating speed diesel engines (above 2000 rev/min) and turbo diesels become more common, cooling the bearings without increasing the cavitation problem will become an important issue[19].

Cavitation within a bearing depends on cavity formation in the fluid and pressure variation below and above the vapor pressure of the lubricant in order for the expansion and collapse of the bubbles to occur. This follows the hydrodynamics of the lubricant and it is a well known practice that negative pressures cannot be sustained in a lubricant. Since basic theory allows positive and negative pressures to develop in the fluid, predicted negative pressure will indicate the position and intensity of any cavity formation[19].

The material of the bearing plays an important role in its resistance to erosion from cavitation. All metals will undergo some sort of strain hardening on the surface during cavitation and in some cases forming a layer of hardened material resisting the collapse of cavities. Under these conditions the bearings will still eventually fail from fatigue, indicating a mechanical failure. Corrosion will attack the material after cavitation damage has begun accelerating the formation of fatigue cracks, rapidly decreasing the life of the bearing. To avoid failure of this nature it is necessary to use a material that shows a high corrosive resistance to the fluid and has mechanical properties that provide high fatigue resistance. A surface treatment has proven to be important. If a thin layer of surface material is added to the bearing, or a strain hardened material such as austenitic stainless steel is used, this will increase its resistance to cavitation damage[17]. A number of factors will play a role in the extension of bearing life including Ultimate Resilience, or a materials ability to sustain repeated strain without cracking. Steel and aluminum alloys and possibly the inclusion of non-metallic materials will be an important factor in designing cavitation resistive bearings. Experiments have shown that high resilience polymeric materials have extremely high resistance to cavitation erosion, greater than any metal[19].

It has been shown that the vibration from automotive engines will produce vibratory cavitation, which is the same type used to produce sonoluminescence in the laboratory. With sonoluminescence and cavitation from engine vibrations sharing the same physical dynamics, producing sonoluminescence near a wall should provide information about bearing damage from collapsing cavities. Learning to predict the conditions that produce cavitation will help machine designers avoid the fluid conditions that support the collapse of bubbles, alternately developing materials that are more resistant to erosion will help to increase the life and reliability of engine bearings.

Chapter Four

Experimental Setup

Producing sonoluminescence in the lab requires a great deal of patience and a willingness to experiment. The experiment can be assembled with some simple equipment probably found in most research laboratories with a minimum amount to purchase. For the most part the experiment can be performed using an oscilloscope, function (audio) generator, amplifier, round bottom flask, piezoelectric transducers and the construction of a simple electric circuit.

Crum and Gaitan[4] were the first to determine the necessary conditions for producing sonoluminescence in the laboratory but it was Putterman[2] and his graduate students at UCLA who refined the technique and made the information available to a large segment of the public. Several articles were published in Scientific American in 1995[2,20] and it sparked a worldwide interest in the phenomenon of sonoluminescence. These articles provide a good starting point for producing SBSL but a great deal of additional information has been made available on the internet by others conducting research in cavitation and sonoluminescence. After obtaining the Scientific American article[2] on producing light from sound, research was begun by examining the experimental setups and instructions for producing SBSL from the web sites that were located. Most of these followed the Scientific American article but provided more detail regarding the construction and explained some of the difficulties in producing SBSL. Most researchers providing information on the Internet were successful in achieving SBSL and all were in agreement that it is much more difficult than implied by the Scientific American article. Much of the information in this chapter used to perform the experiment was found at Robert Hiller's (UCLA, Ref. 21) and Dustin Froula's (Lawrence Livermore Laboratory, Ref. 1) web sites.

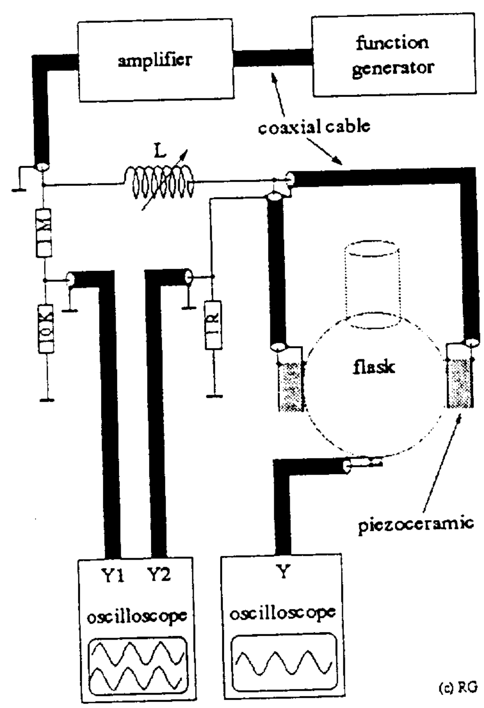

Figure 4.1: Sonoluminescence experiment schematic.

The first step was to acquire the necessary equipment to construct the experiment. A function generator able to produce a sine wave in the range of 25 kHz and an amplifier with the capability to increase the amplitude of the signal above 40 volts peak to peak.

An RLC circuit must be assembled including inductors, resistors, fine gauge wire and coaxial cable. A two-trace oscilloscope was needed to compare the signal in the RLC circuit and microphone transducer. The piezoceramic transducers were purchased from Channel Industries and were designed for producing sonoluminescence. The experiment was performed in a 100 ml round bottom flask. A soldering iron along with a set of small tools were necessary for construction. Figure 4.1 shows a rough schematic of the experiment layout and a detailed list of equipment can be found in Appendix A.

The amplifier and a lab stand to hold the flask were mounted to a board to properly support them. The RLC circuit was then constructed on an electronic prototype board and this was also mounted to the board. Coaxial cable was used whenever it was possible to reduce losses in the wire, 20-gauge wire was then used to make short connections. The inductors and resistors were placed in a configuration according to the diagram in Figure. 4.2. The transducers behave as capacitors so the inductors are necessary to adjust the current and voltage into phase, delivering the maximum power to the transducers.

Ultrasound transducers are phase sensitive and cannot detect a signal in which the phases between different parts of the signal have been mixed. With the signal out of phase this will result in bubbly liquids blocking some of the signal in the ultrasound range. This phase sensitivity of the transducers will ensure coherence, which means the phase relationship between one pulse, and another is unchanged[22].

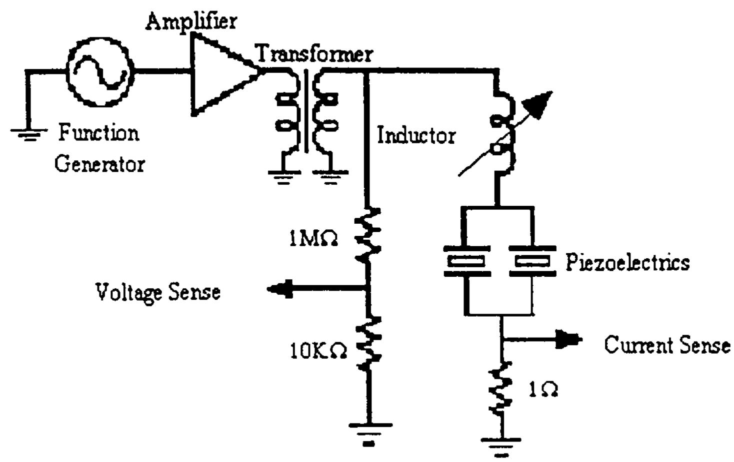

Figure 4.2: RLC circuit diagram.

The electrical inductance is defined as the ratio of voltage to current. The impedance of the transducers has to be matched to the electric circuit or the generated vibration waves will be reflected causing only a fraction of the power to reach the sample[22]. To determine the correct amount of inductance to add to the circuit the transducers were assumed to behave as a parallel plate capacitor and the capacitance was calculated from the following formula:

$$C = K\varepsilon_o \frac{A}{t} = 7.0K\frac{d^2}{t} \tag{4.1}$$

With a dielectric constant K = 1300, transducer diameter d = 0.02 m, a transducer thickness t = 0.005 m, the capacitance was calculated at C = 728 pF. The resonant frequency of the flask was calculated from the following equation to determine the inductance:

$$f_o = \frac{v}{d} \tag{4.2}$$

Using the speed of sound in water, $v \approx 1500$ m/s, the diameter of a 100 ml flask is d = 0.06 m, and an additional 10% added on for distortion from the flask, the resonant frequency is approximately $f_o \approx 27.9$ kHz. With the capacitance and resonant frequency known the inductance necessary to match the capacitance was calculated from:

$$L = \frac{1}{4\pi^2} \cdot \frac{1}{f_o^2 2 \cdot C} = 13 \times 10^{-3} \frac{1}{f_o^2 \cdot C} \tag{4.3}$$

For a resonant frequency of f_o = 27.9 kHz and a capacitance of C = 728 pF the inductance needed to allow maximum power to be transferred to the transducers was calculated to be approximately L = 22.3 mH.

With the approximate inductance determined this was verified experimently using RF inductors. A variable inductor was not available that could handle the current load of several amperes so several different size inductors were purchased to be added in series to obtain the desirable inductance. With the voltage and current held constant the inductance was varied from 15 to 30 mH and the output measured from the microphone transducer on the oscilloscope. A maximum transfer rate of power was found with L = 21.9 mH of inductance in the circuit, this was very close to the calculated value.

It became necessary to add an isolation transformer to the circuit between the amplifier and the circuit when it was discovered the output signal was very distorted. When the system was analyzed it was found that the automotive audio amplifier did not provide for a proper ground and was actually causing a highly resistant short circuit. When the oscilloscope was connected to the circuit it was found that the current load on the power supply would increase sharply. The oscilloscope, function generator and amplifier uses their metal cases as a ground and were now connected in series and slowly shorting out the circuit. An isolation transformer was added between the amplifier and circuit allowing for a highly efficient (near 100%) transfer of power while isolating the circuit from the amplifier. It was constructed with two insulated coils of wire wrapped together within an electromagnetic inductor that allows an exchange of voltage and current from the primary to the secondary wire. It was calculated that a turn's ratio of 5 for each wire was necessary to maintain the polarity of each end of the wire while allowing for the power transfer. Even though the wires are not connected they exchange power with mutual induction through an electromotive force (emf) produced by a change in the current. With this configuration, when the oscilloscope was connected to the circuit it did not cause any change in the current draw or distort the signal.

Piezoelectric transducers are devices that convert one form of energy into another form. In this experiment the driving transducers fixed to the side of the flask convert electrical energy into mechanical energy in the form of vibrations. The microphone transducer attached to the bottom of the flask on the other hand picks up the vibration output from the flask and converts it into electrical energy to be displayed on an oscilloscope. The transducers are made from a ceramic material and work by a voltage being applied between dielectric material in the ceramic that do not conduct electricity but undergo mechanical distortion from the electrical energy.

Before the piezoelectric transducers can be connected to the circuit the oxidation has to be removed with a pencil eraser. About 30 millimeters of 30 gauge wire was then soldered to both sides of the transducers with three wires attached to the side that will be attached to the flask. Care must be taken when soldering the wires to the transducers so that the Curie temperature, which is approximately 300° F, is not reached. The surface should also stay below about 200°F or the ceramic material of the piezoelectric could crack so the soldering iron should not contact the surface for more than a few seconds. Three wires are used so if any of the wires break the transducer does not have to be removed to replace them and to provide a good base for the transducers to match the spherical shaped flask. A fine grade of wire is used to decrease the amount of noise loss from the coaxial cable to the transducer.

The transducers are then attached to the side of flask approximately 180 degrees apart using a quick drying epoxy. Each side of the piezoelectrics are polarized so it is important that when they are attached to the flask the electrodes should be connected in parallel, meaning the positive markings should either be facing each other or pointing away from each other. A third smaller peizoelectric transducer was also soldered with the 30-gauge wire and attached to the bottom of the flask to act as a microphone. This smaller transducer is connected to the oscilloscope and is used to measure the frequency and the amplitude from the driving transducers. Refer to Figure. 4.3 for placement of the piezoelectrics. Only a thin layer of epoxy is necessary but enough should be applied to evenly cover the entire surface of the transducer. It is important to allow the epoxy to dry completely so the transducer is firmly attached to the flask when the experiment is performed.

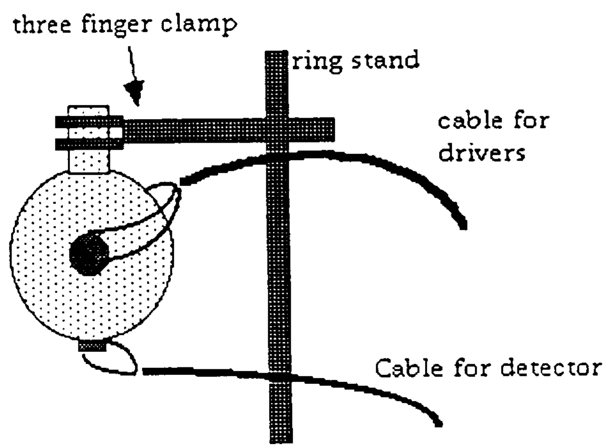

Figure 4.3: Piezoelectric transducer placement on the flask.

Choosing the correct flask to perform the sonoluminescence experiment is very important to achieve successful SBSL. A 100-ml round bottom flask was selected because it was the most common type used in other experiments. Although a popular model, it was later found that this was a poor flask for producing SBSL. Most flasks are inexpensive so a variety can be obtained and tested. To determine if a flask is good for producing SBSL it should be tested before performing the experiment and can be assigned a numerical value based on its probable ability to generate sonoluminescence. This value is known as the Quality Factor and is mostly based on the type of flask used along with some other minor parameters in the experiment. The Quality Factor or Q will be discussed more in Chapter 5 including a description on how to obtain its value provided in Appendix B.

Two 100-ml flasks, one having a 24/40 neck and the other a 14/20 neck were purchased. The first number signifies the diameter of the neck and the second is its height in millimeters. A small neck flask is desirable because with less glass material there will be less dampening of the vibrations from the transducers. Considerable difficulty was encountered in determining the resonant frequency with the large neck flask but when switched to the 14/20 neck flask that problem vanished. It is critical to point out that: SBSL most likely cannot be achieved with a large neck flask.

With the piezoelectric transducers cemented to the sides, the flask was hung in a clamp but this method was found to be too rigid. Information obtained from the Internet suggests suspending the flask with wires because the padded clamp holds the flask too tight thus dampens the vibrations. Later, the flask was hung with wires from the clamp, which seemed to help the problem but made it difficult to fill and empty the flask.

For sonoluminescence to occur the concentration of dissolved air in the water must be controlled. Dissolved air in the water will have a small effect on the velocity of sound in water but more importantly changes in pressures produced by the transducers will force dissolved air out of the water forming bubbles[22]. The concentration of air should be around 20% saturation and this can be obtained by either boiling the water for a set period of time or using a vacuum pump to decrease the air pressure in a flask of distilled water forcing air from the water.

For the purpose of this experiment boiling the water was the most practical of either methods. A 1000-ml Erlenmeyer flask was filled with about 300 ml of distilled water and capped with a rubber stopper with a pipette inserted in it allowing it to vent. This water was then brought to a roaring boil for at least 15 minutes. The flask was then sealed and removed from the heat allowing it to cool and forming a strong vacuum within the flask degassing the water. This can be accelerated with refrigeration if available or just by running cool water over the flask. Cooling the water to just a few degrees Celsius will also produce a much brighter light. This will actually degas the water to well below the optimum 20% but in the process of transferring the water from the Erlenmeyer flask to the round bottom flask for the experiment should re-gas the water to an acceptable level for SBSL to occur.

With the experiment fully assembled, the exact resonant frequency of the flask of water could be determined. It was calculated previously at approximately 28 kHz and from this starting point the exact natural frequency for a particular flask could be found. This was a good time to check if the power levels are large enough to produce SBSL. If the amplitude of the driving transducers cannot reach well over 100 volts peak to peak then the inductors may not be properly matched to the circuit. This process is easiest with fully gassed water in the flask because the more bubbles that cavitate the easier it is to find the maximum amplitude. With the flask filled, the microphone piezoelectric transducer connected to the oscilloscope and the driving transducers wired to the function generator through the circuit the frequencies were scanned in 10 Hz increments until the maximum displacement was shown on the oscilloscope. It is sometimes helpful to draw some water into a syringe and spray it into the filled flask to create additional bubbles. It should be easy to see the bubbles cavitating and a lot of noise is generated when the resonant frequency is found. Several points of resonance will be discovered and it should be noted that the point with the maximum amplitude might not always be the best for producing SBSL.

When the round bottom flask was to be filled, the water should be carefully poured down the side of the flask without splashing. Pouring the water will re-gas it to a slightly higher level but any excessive splashing of the water will produce a higher concentration of dissolved air than is desired. This extra air will dampen the vibrations from the transducers decreasing the likelihood of producing SBSL. The flask should be filled until the water level is at the bottom of the neck forming a sphere of water.

The room has to be prepared before SBSL can be observed. Ideally the room should be perfectly dark since the light output that will be viewed is very small and not that bright. It was thought that with the room in complete darkness it would be difficult to see what was happening however after a 20 minute period to allow ones eyes to adjust to the darkness, the experiment could proceed. It was found best to perform the experiment at night but this too proved difficult because some light from outside the room leaked in and because of the lighted displays of the equipment. Rearranging some of the equipment with the displays pointing away was necessary and positioning the experiment so that the background behind the flask was not lit was also very helpful.

After the resonant frequency has been determined and the flask filled with degassed water the sonoluminescence threshold has to be located. Starting with no bubble in the flask the sine wave displayed on the oscilloscope should be clean, if not more than likely the water needs to be degassed again because the microphone transducer picks up very small cavitating bubbles elsewhere in the flask. The power level should be set very low, just enough to trap a bubble in the center when it is injected into the flask. The power level should be raised slowly until the bubble completely collapses and disappears, this is the point just past the upper sonoluminescence threshold. The power should be reduced slightly and another bubble injected into the water. The frequency should next be adjusted until the amplitude of the microphone transducer is at a maximum. If the bubble dances around then in most cases the power level has to be adjusted or the water may not be properly degassed. A dancing bubble is not always a bad sign for sometimes the frequency has slightly changed and a small adjustment of only a few of Hz's can stabilize the bubble in the center.

Figure 4.4 was a chart determined by Crum to show the regions in which SBSL will occur with respect to signal amplitude. This graph does not give any indication that this region is very small compared to the range the amplitude is capable of achieving. Figure 4.5 gives a good representation of the power levels needed to produce SBSL compared to the gas concentration of the water. The gas concentration of the water is a

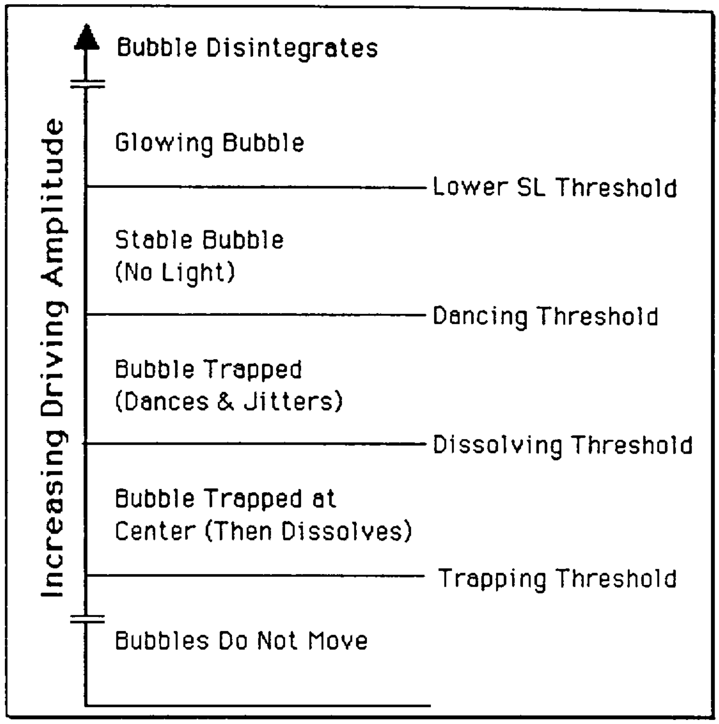

Figure 4.4: Sonoluminescence threshold verses driving amplitude.

careful balance of having enough dissolved air in the water to form a bubble but not too high of a concentration that dampens the vibrations from the transducers. It was mentioned that boiling the water will reduce the concentration of dissolved air to nearly zero but when it is added to the round bottom flask may not re-gas it enough. This problem was resolved by using a syringe to add more air to the water but another alternative is to allow the flask that the water is boiled in to sit uncovered for a period of time allowing it to slowly re-gas. It has been suggested that the degassed water can sit in an uncovered flask for up to one day and still be able to produce SBSL.

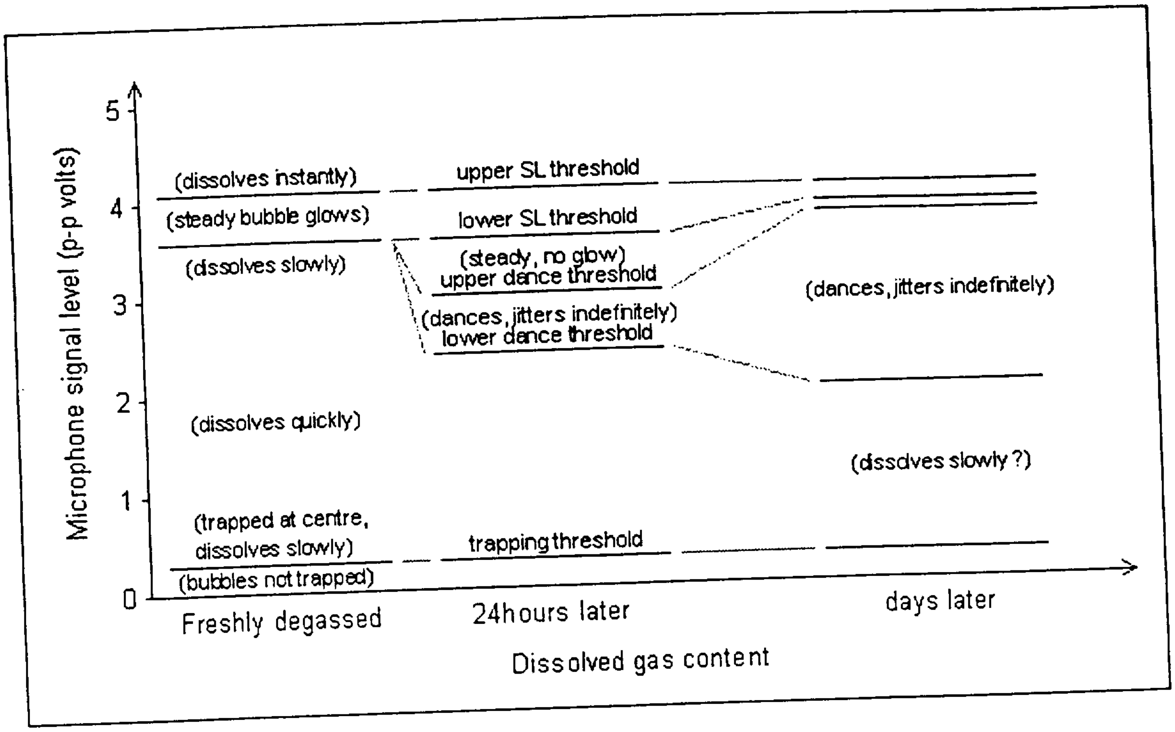

Figure 4.5: Amplitude required versus dissolved air concentration for SBSL.

After some practice with adjusting the amplitude and controlling the trapped bubble SBSL has the best opportunity to be achieved. This is probably the most time consuming and frustrating part of the experiment in which failure is the most common outcome of each try. It is better to watch the oscilloscope, find the frequency range and then listen for the sound of cavitation. A web site was located that provides an audio recording of SBSL occurring, this was extremely helpful and was used as a means to assess that SBSL used most likely had been achieved.

Chapter Five

Final Remarks

The art of producing sonoluminescence in the laboratory proved to be a very frustrating ordeal and resulted in a series of failures. It has already been mentioned that trying to follow the Scientific American article even with the additional information that was uncovered still proved to be a very difficult task.

Throughout the construction process numerous researchers were contacted about the experimental setup. What proved to be the most problematic was the electric circuit itself. A very distorted signal was observed with a lower amplitude than was expected. This was overcome with help from some experts in electronics. They determined that an isolation transformer was needed, made other suggestions and suggested techniques to better understand how to operate the electronic equipment. It is now clear that there are a number of peculiarities involved when working with an electric circuit capable of handling several amperes of current in the ultrasonic frequency range.

It was discovered that after the power levels were raised to several volts peak to peak, as measured by the microphone transducer attached to the bottom of the flask, a bubble could be captured in the center of the liquid and held there for a short period of time. A number of interesting things would begin to happen at that point. For example it was found that it was easier to capture a bubble when increasing the frequency from below the resonant range as opposed to lowering the frequency from above the resonant point. In some cases air would not have to be added from the syringe but a bubble could be coaxed from the dissolved air in the water just by slowly raising the frequency to the point of resonance. The bubble could be held in the center of the flask for several minutes before it would either dissolve or start to drift to the side of the flask. The bubble drift was at the outset of the experimentation and this was initially attributed with the point of resonance. Several different points of resonance were found when the fully gassed water was used in the experiment. This information was then applied to the experiment using degassed water. However, because the exact resonance point was unknown, the frequency was adjusted in an attempt to bring the bubble back to the center. Unfortunately it would usually dissolve. Sometimes, when one of the other points of resonance was used instead of the maximum, improved results were obtained. For the most part the drifting problem ended.

After working on trapping an acceptable bubble in the center of the flask and getting it to cavitate, an enormous amount of time was spent trying to induce it to glow. The Scientific American article (Ref. 20) provided little information for this part of the investigation, hence considerable reliance was placed on techniques developed by other researchers who posted them on their web sites. Photographs were obtained of what SBSL should look like and an audio recording (which proved the most helpful) was also secured.

Throughout this period many observations of the bubbles were made and the effect of acoustic forces on them was also observed. While trying to determine the resonant frequency of the flask with the fully gassed water it was noticed when the amplitude was increased sometimes the bubbles that were attached to the side of the flask would separate from the wall. When this would happen the bubbles would either dissolve or reattach to the side of the flask at another location. It was found that the bubbles were very unstable in the fully gassed water, even with the frequency held steady the bubbles would dance around wildly. This shows the possibilities of employing a device upstream of the cavitation zone to force gas and vapor cavities to dissolve before they contact any surfaces.

The quality factor (or simply Q) of the flask, which is the efficiency of a cavity, is determined by measuring the energy stored in the bubble divided by the average power loss. Equation (5.1) provides the mathematical formula to calculate the Q of the spherical cavity but it is actually easier to determine it graphically from data acquired from the oscilloscope as shown in Appendix B.

$$Q = \frac{2\pi f_o E}{\Delta E} \tag{5.1}$$

The Q of the 14/20 100-ml flask was determined to be approximately 216. This is a value that should be good enough for producing SBSL but is not really at the optimum level. The higher the Q the easier it is to produce SBSL because less acoustical energy is necessary to trap the bubble. As mentioned earlier the two largest factors that affect the Q are the neck and supporting structure for the flask. The neck of the smallest flask used for a 100-ml flask that could be located. However, it is hypothesized that by hanging the flask using thread from the clamp the Q could be increased a little.

The laboratory in which the experiment was performed was not adequate for measuring some of the parameters of sonoluminescence. Accordingly the parameters will be given some explanation. The driving factor for investigating sonoluminescence is the enormous amount of energy involved with the phenomenon. This massive amount of energy is developed from the catastrophic collapse of the bubble. The following is a quick review of the SBSL phenomenon. The bubble starts out with a diameter of several microns and with acoustic pressure undergoes an expansion process forming a near vacuum inside. The surface of the bubble fails under tensile stress causing a violent collapse sending a shock wave traveling through the cavity.

Much of the current research on SBSL has been on determining, predicting and understanding the temperatures produced by these shock waves. As more information becomes available about SBSL it begins to appear that the energy released is much higher than many earlier estimates and with continuing research these numbers should become more accurate. Table 5.1 gives some of the temperature estimates along with the time line and the people who made these measurements or calculations. These discoveries in sonoluminescence made by these researchers will prove to be very helpful to engineers studying the effects of cavitation.

Year	Researcher	Temperature (Kelvin)	Methodology
1917	Lord Rayleigh	Assumed a constant temperature	Boyle's Law
1950's	B. Noltingk & E. Neppiras	Up to 10,000	Adiabatic compression calculations
1986	K. Suslick	5,000	Chemical rate equations
1991	S. Putterman & R. Hiller	72,000	Measuring the light spectrum experimentally
1995	S. Putterman & R. Hiller	1,000,000	Measuring the light spectrum with shock wave theory
1996	W. Moss	10,000,000	Numerical simulations

Table 5.1: Results of sonoluminescence temperature research.

Performing SBSL is ideal for cavitation experimentation because it is a continuous process in which a single bubble forms and collapses repeatedly for billions of cycles. This way the energy released from one cavitating bubble can be determined and the potential damage to an object studied. During MBSL many scattered bubbles will glow in which each bubble forms and collapses once or just a few times and then dissolves reforming elsewhere. With MBSL the cavitation is at a greatly reduced level compared to SBSL[23].

The main focus of this research was to first perform SBSL in the laboratory, link this phenomenon to cavitation damage done to diesel engine bearings and determine if a bubble could be forced to cavitate near a surface. It has been shown that most damage done to engine bearings is in the form of vibratory cavitation, the same type that produces sonoluminescence, so SBSL could prove to be a low cost tool for studying cavitation.

An article in the journal Physical Review E (Ref. 24) was recently obtained that could provide some of the necessary information for performing this research. It discusses a sonoluminescence experiment performed at UCLA with an argon cavity fixed to a thermocouple wire. For the experiment, a hemispherical cavity is attached at an intentionally made defect in the thermocouple wire. Producing SBSL is more difficult in this case because the hemispherical cavity is about 10 times larger then an unattached bubble and the surface of the wire is damaged while performing the experiment. To assist in viewing the glowing cavity the bubble is doped with a heavy noble gas (xenon) and the temperature of the gas is lowered to 220 K, thus increasing the light intensity. The light spectrum from the surface cavity is very similar to the SBSL experiment and is still in the ultraviolet region. Since a thermocouple wire was used to suspend the cavity it was possible to measure the temperature but the junction of the wire was several millimeters away from the collapsing cavity. When the bubble was present the temperature would rise about 10 degrees but would return to the ambient temperature of the water when is was gone. A similar experiment was also performed with a copper surface suspended near the center of the cell. Multiple light emitting bubbles were observed attached to its surface and the experiment was allowed to run about 1 hour. As expected cavitation damage was observed with a scarred surface and a small hole cut into it with small copper fragments lying on the bottom of the cell. This cavitation damage would suggest the collapsing bubbles produce jets.

This research definitely suggests the great potential that sonoluminescence holds for studying cavitation damage to surfaces. With some alterations to the current experimental setup in the laboratory such as using a cylindrical cell instead of the round bottom flask, adding a high speed camera and a photomultiplier tube for measuring the light spectrum, many different experiments could be readily carried out.

The most logical next step would be to increase the power levels to get out of the lower SBSL region and produce very stable sonoluminescence with a steady output of light. This could be accomplished by adjusting the inductance, adding an additional amplifier and/or possibly the best solution could be to replace the inductors with a step transformer. The transducers are more reactive to the voltage than the current so a transformer could efficiently deliver the most power from the amplifier.

Several experiments could be performed if this level of sonoluminescence is achieved. The first would most likely be to reproduce the UCLA experiment of SBSL and MBSL near a surface and test the affect of cavitation on different types of materials. Possibly the level of cavitation could be measured just as the spectrum of sonoluminescence with the photomultiplier tubes. There are also many groups doing computational studies in sonoluminescence including a member of the tribology group from the University of Toledo. Data from the experiment could be used to compare results with numerical solutions and provide data for further computational study. Some computational and experimental research could be conducted based on a numerical study performed at The Chinese University of Hong Kong (Ref. 25) questioning whether shock waves are important to SBSL. Shock waves were previously considered to cause the most cavitation damage and this may not always be the case. The results of the study show that shock waves are present during the initial cycle of SBSL when the cavity is comprised of air. During the transient argon-rectifying stage when the bubble is cleansed of oxygen and nitrogen leaving behind a gas of mostly argon the shock waves may be replaced with smooth compression waves. Compression waves increase the energy level inside the bubble over a relatively wide region of the gas developing high temperatures. Their data does show a peak temperature of about 80,000 K with the compression waves rather than shock waves. Determining if shock waves are absent during argon SBSL could provide much needed data about cavitating bubbles.

After this research has been performed a much more ambitious experiment could be the development of a cavitation rig to test theories along with applying acoustic knowledge for the formation and control of cavitating bubbles. This could range from acoustically forcing cavitation in a moving stream of fluid to controlling or stopping cavities formed from machinery. This will prove to be a great task but the payoff in knowledge gained in cavitation would be enormous in this age of turbo machinery operating at higher speeds and finer tolerances.

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Appendix A

Sonoluminescence Equipment

The following equipment was used to produce single bubble sonoluminescence in the laboratory. Most of this equipment was purchased to primarily support the SBSL experiment with some equipment borrowed from other departments.

- Piezoelectric Transducers – Sono Kit purchased from Channel Industries, Inc., Santa Barbara, CA, (805) 967-0171, includes 2 large driving and 1 small microphone transducers.
- Wavetek FG3B Function Generator – frequency output range from 0.2 Hz to 2.0 MHz and allows for three decimal place accuracy at 27 kHz.
- Urban Audio Works UZ-2750 Amplifier – 400 Watt total output with 100 Wx2 rms output. Capable of amplifying frequencies from 5 to 50 kHz powered by a 12 VDC power supply.
- Wavetek 85XT Digital Multimeter – Measures VDC, VAC, current, resistance and frequency. 4.5 digit LCD and an accuracy of plus and minus 0.5%.
- Tektronic TDS 220 Oscilloscope – digital 2 channel 100 MHz with 1 GS/s sampling rate.

- HP 6012B DC Power Supply – 0-60 VDC and 0-50 A, capable of 1000 Watts to power the amplifier. Only 12 Volts at a maximum of 10 amps was necessary but this one was available.
- Lutron TM-902C Thermocouple Reader – Monitoring the temperature of the piezoelectric transducers.
- Cimarce Laboratory Hot Plate – For boiling the distilled water.
- Weller WCC 100 Soldering Iron
- 1000 ml Pyrex Erlenmeyer Flask
- 100 ml Pyrex Round Bottom Flask with small neck
- RG 58 Coaxial Cable
- 18, 22 and 30 gauge wire
- 1 M, 10 k and 1 ohm resistors
- Inductors – Several in series to total approximately 22 mH or a variable 15-30 mH inductor will work if it is capable of carrying 1 amp of current.
- Isolation transformer
- Laboratory stand with clamp
- Distilled water
- Syringe
- Set of small tools
- Electronic Prototype Board
- Rubber stoppers, pipettes and cleaning detergent for flasks

Appendix B

Measuring the Quality Factor

The quality factor (Q) is a measure of the efficiency in which SBSL can be produced for a given signal power level. There are other factors involved with the determination of the Q but the most important is the geometry of the flask used. The following graphical method should be adequate to determine whether the flask that is chosen will have a high enough value of Q to produce SBSL[1].

Once the experiment is assembled including the transducers attached to the flask, the oscilloscope should be connected to the circuit and the induction adjusted to get the circuit in phase. Next the oscilloscope should be connected to the microphone transducer attached to the bottom of the flask. If possible, it is helpful to set the oscilloscope to display the amplitude and frequency in the numerical readout.

Use the fully gassed water in the flask and determine the resonance point as described earlier in the text. When the maximum amplitude is found, adjust the frequency in approximately 10 Hz increments plus and minus the point of resonance until about 10 points of data are collected. At each increment record the amplitude from the microphone transducer and graph the data. The graph should form a parabolic plot.

For this demonstration Table B.1 shows the data that was collected from the 14/20 100-ml flask and Fig. B.1 is the corresponding graph.

Frequency (kHz)	Amplitude (volts p-p)
28.08	6.1
28.14	4.9
28.20	6.2
28.25	4.9
28.30	6.5
28.35	17.5
28.39	21.6
28.44	14.9
28.47	12.0
28.50	11.2

Table B.1: Data for determining the quality factor.

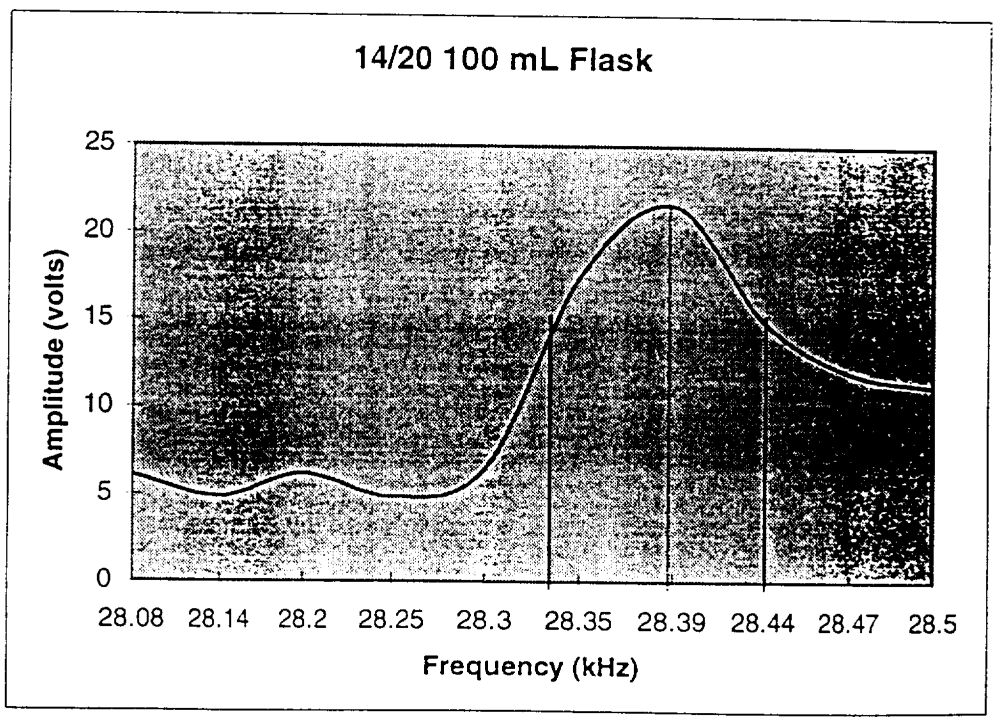

Figure B.1: Amplitude vs. the frequency for determining the quality factor.

The full width half maximum (FWHM) is then calculated by dividing the maximum amplitude by the square root of two and find this point on the graph at the resonant frequency. At this FWHM amplitude find the frequencies on the data line that correspond to this amplitude. Measure the difference between these two frequencies and divide the maximum amplitude by the difference to produce the quality factor. The following equations will give a mathematical description of the graphical process.

$$FWHM = \frac{resonant\ amplitude}{\sqrt{2}} = \frac{21.6}{\sqrt{2}} = 15.27 \tag{B.1}$$

At amplitude of 15.27 the data line crosses the frequencies 28.44 and 28.34.

$$\text{difference} = 28.44 - 28.34 = 0.10 \tag{B.2}$$

The quality factor is just the FWHM divided by the difference.

$$Q = \frac{FWHM}{difference} = \frac{21.6}{0.10} = 216 \tag{B.3}$$

A Q above 500 offers the best conditions for producing SBSL but a value of 216 should just be adequate. The main disadvantage of a low number is that more power from the amplifier will be necessary to view a glowing bubble.